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Towards a methodology to formulate sustainable diets for livestock: accounting for environmental impact in diet formulation

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Abstract

The objective of this study was to develop a novel methodology that enables pig diets to be formulated explicitly for environmental impact objectives using a Life Cycle Assessment (LCA) approach. To achieve this, the following methodological issues needed to be addressed: 1) account for environmental impacts caused by both ingredient choice and nutrient excretion, 2) formulate diets for multiple environmental impact objectives, and 3) allow flexibility to identify the optimal nutritional composition for each environmental impact objective. An LCA model based on Canadian pig farms was integrated into a diet formulation tool to compare the use of different ingredients in Eastern and Western Canada. By allowing the feed energy content to vary, it was possible to identify the optimum energy density for different environmental impact objectives, whilst accounting for the expected effect of energy density on feed intake. A least cost diet was compared with diets formulated to minimise the following objectives: non-renewable resource use, acidification potential, eutrophication potential, global warming potential and a combined environmental impact score (using these four categories). The resulting environmental impacts were compared using parallel Monte-Carlo simulations to account for shared uncertainty. When optimising diets to minimise a single environmental impact category, reductions in the said category were observed in all cases. However, this was at the expense of increasing the impact in other categories and higher dietary costs. The methodology can identify nutritional strategies to minimise environmental impacts, such as increasing the nutritional density of the diets compared to the least cost formulation.

Introduction

In commercial pig farming systems it is typical for nutritionist to formulate diets for economic objectives [1] such as revenue / feed cost or feed cost / kg live weight (LW) gain [2]. This is most commonly done through the use of linear programming. More recently however, sustainability objectives rather than economic ones have increasingly come into consideration in diet formulation. There has been an increased interest in the quantification and mitigation of the environmental impacts of the livestock industry [3]. Assessing farming operations in more ways than just their economic "bottom line" may become more important as part of efforts to improve the sustainability of livestock systems.

For pig production systems feed production and manure management are the main sources of environmental impacts [e.g. (4–6)]. Life Cycle Assessment (LCA) is a generally accepted method to evaluate holistically the environmental impact during the entire life cycle of a product or system [7], and there are many metrics through which environmental impact can be quantified. Carbon footprint or Global Warming Potential (GWP) is the metric that has received the most attention in the recent past [8]. Analyses of livestock systems using LCA have shown monogastric animal production systems cause less GWP than meat production from ruminants, whether measured per kg of product or protein produced [9–11]. Pork production is however, associated with relatively high levels of other environmental impact categories, including Non-Renewable Resource Use (NRRU), Acidification Potential (AP) and Eutrophication Potential (EP) [9,10]. The production of feed is responsible for the majority of GWP (up to 65%) [4,6,12] and NRRU (up to 90%) [5] resulting from pig farming systems. The majority of AP and EP caused by pig production is due to emissions during manure storage and application, as a direct result of the excretion of N and P by the animal [6,13,14]. As such, the ingredient and nutritional composition of the diets are extremely important considerations when quantifying the environmental impacts of pig production systems.

The objective of this study was to develop a novel methodology which enables pig diets to be formulated explicitly for environmental impact objectives using an LCA approach, whilst not penalising animal growth. The methodology was associated with the following challenges: 1) how to account for environmental impacts caused by both nutrient excretion and ingredient choice, 2) how to formulate diets for multiple environmental impact objectives, and 3) how to identify the optimal nutritional composition of diets for different objectives. An LCA model for pig farming systems was integrated into a diet formulation tool. The LCA model was then used to quantify the potential reductions that can be made to the environmental impact of Canadian pig farming systems through explicitly optimising diets for this purpose in a diet formulation tool.

Materials and Methods

The system under consideration

Modern pig farming systems can be considered to have 3 distinct production phases; 1) gestation and farrowing - where piglets are produced by breeding sows, 2) the nursery or weaning phase when pigs are separated from their mother and 3) the grower/finisher (G/F) phase where pigs are fattened from around 30kg to slaughter weight [(15)]. Figure 1 shows the major components of this system when considered in an LCA model; from the production of feed ingredients to animals shipped from the farm gate for slaughter. There were three main compartments of material flow considered in the LCA model: 1) the production of feed ingredients, 2) the consumption of feed, energy and other materials for on-farm pig production and 3) the storage and land application of manure. Benchmark data from 2012 on Canadian pig farms showed that 78% of feed consumed per pig produced and at least 75% of the environmental impacts occurred during the G/F phase [(5)]. Attention therefore was given to formulating diets only for the G/F phase of production. Diets were formulated in two scenarios for pig production systems in Eastern and Western Canada because the main ingredients used in their typical diets are not the same. Pig diets in Eastern Canada are typically based on maize similar to USA pig diets [(16)], whereas pig diets in Western Canada use wheat and barley as the main cereal component/s [(17)].

The LCA model

The environmental impacts resulting from all diets formulated in this study were calculated using an LCA model of pig systems in Eastern and Western Canada [(5)]. Some aspects of this model were also included as part of the diet formulation process (see *Diet formulation rules*). The details regarding the main components of the LCA model of Canadian pig farming systems are provided below. The system boundaries of the LCA were cradle to farm-gate and the functional unit was 1 kg expected carcass weight (ECW) [(5)]. The breeding and nursery production stages were treated as independent to the G/F phase in this study and remained constant for all comparisons made.

Feed production

The average environmental impacts per kg of ingredient for all ingredients used in the G/F diets can be found in Table 1. Important causes of environmental impact in the feed supply chain for pigs include: fossil fuel inputs for fertilizer production, emissions resulting from the spreading of fertilizers, fossil fuel use for field operations, energy inputs to processing (drying, grinding etc.) and transport [18]. When modelling a complex supply chain, as is the case for animal feed, the inputs to the process (wheat, water, energy etc.) are shared between the different co-products resulting from these processes, and the environmental impacts associated with them must be allocated. Economic allocation was used as the methodology for co-product allocation throughout the feed supply chain as advised in the FAO LEAP recommendations [19]. The price ratios found in the supplementary material S1 were used for the purposes of economic allocation. Life Cycle Inventory (LCI) data for the production of major crops was adapted from a previous LCA on Canadian crop production [20]. LCI data for amino acids lysine, methionine, threonine and tryptophan were obtained from an LCA study on the impact of amino acids in pig diets [21]. LCI data for the production of minerals dicalcium phosphate, salt and limestone came from the Ecoinvent databases [22]. LCI data for maize DDGS from Canadian sources was not available and therefore was adapted from data representative of ethanol production in the USA [22] assuming the use of Canadian maize and typical electricity mix. The LCI for bakery meal was based on data provided by a large retailer of bakery meal (Sugarich, per comm, 2015) and adapted for a Canadian scenario [23]. Surplus material from bread production is a large proportion of the material used for bakery meal sold for use in monogastric diets (Sugarich, per comm, 2015) and was used as a representative input to bakery meal in this study. The LCI for the production of 1 kg bread was adapted from the LCA food database [24] with the input of Canadian wheat and energy sources. A price ratio of 10:1 was assumed for bread and surplus material, with an average 10% of material collected as surplus from the bread supply chain either during the production process or discarded at the supermarket (Sugarich, per comm, 2015). Processing inputs for packaging removal, drying and grinding were estimated to be 20 kWh electricity and 62 kWh natural gas per tonne of material processed (Sugarich, per comm, 2015). LCI data for meat meal was adapted from a previous LCA study on rendering, the yields by mass from rendering were assumed to be 57.7% for fat and 42.3% for meat meal [25]. The price ratio of rendered fat: meat meal was assumed to be 1.22 [23]. The LCI data for wheat milling was adapted from Ecoinvent [22] in order to represent Canadian energy inputs. Bread flour yields was estimated to be 73% on average, with remaining material flows of 2% wheat germ, 12.5% wheat shorts and 12% wheat bran [26]. A price ratio of 1:0.11:0.22:0.44 was assumed for wheat flour: wheat germ: wheat shorts: wheat bran. This was based on the expectation that flour would provide around 90% of the gross margin for a typical milling operation[27] and Canadian price data for the co-products from wheat milling as animal feed [23].

Manure model

The manure model estimated the emissions of CH_4, NH_3, N_2O, N_2 and NOx which occurred during housing, storage and application as well as the leaching of NO_3 and PO_4. Indirect N_2O formation resulting from NH_3 and NOx emissions and NO_3 leaching were also modelled in accordance with the IPCC principles [28]. Manure was assumed to remain in the barn for up to 7 days; it was then transferred to outside storage (except in cases where storage was a pit beneath the barn). It was assumed to be applied to land twice annually in spring and autumn. The model of NH_3 emissions for housing and storage was based on a previous model of NH_3 emissions from pig production in Canada [29]. A tier 2 IPCC methodology was adopted for emissions of CH_4, N_2O, NOx and NO_3, but adapted to reflect small N losses from housing. As average ambient temperatures were considered to be < 0 ˚C during winter [30], emissions during this period were considered negligible for outside storage methods. The proportional mix of floor types in pig housing, storage and application techniques in each region was based on information from the Livestock Farm Practice Survey [29], as well as Statistics Canada records regarding the storage and application of swine manure [31,32]. All N, P, K excreted in feces or urine was assumed to be applied to land as fertilizer, once losses during housing and storage were accounted for. Manure applied to land was assumed to replace the need to apply equivalent synthetic fertilizers at a rate of 0.75, 0.97 and 1 for N, P and K respectively [33]. The proportional mixture of the types of synthetic fertilizers replaced by the NPK content of the manure in each region was derived from sales figures for Eastern and Western Canada to assume a regional average fertilizer mix [34].

Farm performance

With the exception of feed intake during the G/F stage and carcass yield the baseline herd performance characteristics (litter size, mortality etc.) used in this study were as those modelled for pig systems in Eastern and Western Canada in a previous regional LCA study [5]. All characteristics of herd performance other than average feed intake and carcass yield were assumed to be independent of feed composition in the G/F production stage [23]. While this represents a simplification made for the purposes of a modelling exercise it is valid for the scenarios modelled here. All diets formulated were nutritionally balanced and would not be expected to have implications for herd health status or mortality during the G/F phase. It is reasonable to expect that other model inputs such as on farm energy use are independent of feed composition. The on-farm energy consumption data was adapted from a detailed study of energy consumption in conventional pig housing systems in Iowa [35], as there were no equivalent data for Canadian systems available. To reflect longer and colder Canadian winters in comparison to Mason City, Iowa (which was used in the Lammers et al. (2010) calculations), larger loads of Liquid Petroleum Gas (LPG) for heating were assumed to be required to maintain adequate barn temperatures. Based on average temperature data for Mason City [36], and regional data for Eastern and Western Canada [30] the LPG inputs for heating barns in Eastern Canada were estimated to be 25% higher than in the Iowa case study. LPG input for heating in Western Canada was assumed to be 25% larger than for Eastern Canada. These represent approximations as a previous sensitivity analysis showed that the model was not very sensitive to the assumptions made regarding LPG use for any of the impact categories tested here [5]. The mix of electricity generation in the LCA was the national mix for the Canadian grid [37]; this was assumed for all Canadian unit processes in the LCA.

Quantifying environmental impacts

The environmental impacts of the system were quantified by the LCA using four environmental impact categories. Three of these categories quantified negative impacts resulting from emissions caused by the system; AP, EP and GWP. We included GWP as it has received the most attention in efforts to quantify the impact of livestock systems. The impact categories AP and EP were considered as they quantify the main environmental impacts which result from the storage and spreading of animal manure. The fourth impact category quantified the systems use of NRRU and was included because of the relatively high usage of cereals and oil seed meals in pig diets, which have a significant input of resources such as fertilizers [3].

System GWP was quantified in CO_2 equivalents (eq) on a 100 year timescale using the IPPC methodology [28]. The methodology of accounting for GWP caused by land use change in this study followed the PAS 2050 guidelines [38]. The methodologies for calculating AP (SO_2 eq), EP (PO_4 eq) and NRRU (Sb eq) were established by researchers at the Institute of Environmental Sciences at Leiden University (CML) [39]. This methodology was chosen as it is designed to quantify these impact categories on a global scale; importantly accounting for the long term impacts of airborne emissions on global levels of substances which contribute to AP and EP. The CML methodology for normalising different types of environmental impact [40] was also utilised to formulate diets to minimise the combined environmental impact score of the system. The impacts which result from a process are normalised against a reference which is an estimate of the total annual level of global emissions and resource use caused by human activity [40]. The normalised scores for AP, EP, GWP and NRRU were then combined additively, with equal weighting to generate a combined environmental impact score in the diet formulation tool. Equal weighting was adopted in this example to ensure large increases in an individual environmental impact category did not occur when optimising to minimise the combined environmental impact score. The cradle to grave environmental impact calculations were performed in the software package SimaPro 7.3.3.

Diet formulation rules

A diet formulation tool was developed which predicted the environmental impacts for each category resulting from G/F diets for the feed supply chain and manure management. The tool also quantified the feed cost per kg LW gain for each solution. The tool formulated diets using linear programming in Microsoft Excel® with the software plug in open solver [41]. Nutritional values for all ingredients in the diets were primarily taken from the Stein Monogastric Nutrition Laboratory ingredient matrix [42]. In cases where certain values were missing (or ingredients themselves were missing from the matrix), values from the NRC 2012 feed ingredient tables [43] and the Premier Nutrition Atlas [44] were used. All of the G/F diets were formulated with four feeding phases (starter, grower, finisher and late finisher); this reflected typical feeding programs adopted by commercial pig operations in Canada [5].

The predicted start weight of the pigs in the diet formulation tool was fixed at 27.4 kg with a finish weight of 124 kg for the G/F phase, based on benchmark data collected for a previous LCA study of Canadian pig farming [5]. Diets were not formulated for a fixed nutritional density, rather this was an outcome of the solution for a specific objective. The average feed intake per pig for each diet within a feeding phase was predicted based on meeting the animal's requirements for growth. The net energy (NE) requirement for each feeding phase was defined in compliance with the NRC 2012 animal requirement tables [45]. Minimum nutrient levels in g/MJ of NE were then defined for each feeding phase, so that the digestible protein and macronutrient content of the feed would not be limiting for animal growth [45]. It was thus assumed that feed intake was driven by the animals need to meet its daily energy requirements; as such feed intake increased when diets of reduced energy density were fed [46,47]. The average predicted NE intake was constant for all diets. As all diets were nutritionally balanced the animals were expected to spend the same average number of days in the barn over the course of the G/F phase. When diets were formulated at reduced energy density, daily feed intake was expected to compensate for this. Any effects the increased daily intake may have had on gut fill were taken into account [23].

Average ingredient prices and availability in Ontario and Manitoba for 2015 were provided by Trouw Nutrition, (derived from Statistics Canada data [48] - see supplementary material S2 for the list of available ingredients and price ratios in each region). These were used to represent typical diet formulation scenarios for Eastern and Western Canada. Ontario and Manitoba produced around 24% and 23% of the total pigs marketed in Canada in 2011 respectively [49]. Importantly maize was not considered as an available ingredient for the Western diets as is typical in many scenarios in this region; similarly barley was not considered as an available ingredient in the Eastern diets (A. Pharazyn per comm, 2015).

The average gain: feed ratio over the G/F phase in the benchmark data for Canadian pigs was 0.365 [5] with feed intake 264 kg per pig based on the mean start and finish weights. This was used as a starting point for the assumptions on average feed intake in this study. A dietary specification was defined which represented an industry standard to ensure feed: LW gain ratio was minimised within reasonable commercial constraints. The specifications of this “typical” diet are found in table 2 and it was assumed that this diet ensured an average gain: feed ratio 0.365. Lower limits were defined for the nutritional density of the diets for each feeding phase. These were set at 95% of the energy content of the typical industry diet in the first 2 feeding phases and 92.5% for the latter 2 feeding phases. These restrictions were to ensure feed intake would not be restricted by gut fill, which can be caused by diets of lower nutrient density which contain a larger proportion of bulky feed [46]. These minimum specifications of the G/F diet for each phase can also be found in table 2. For each ingredient a maximum inclusion rate was defined for each feeding phase in order to account for any anti-nutritional properties or other negative impacts on animal performance due to variability. These limits were based on guidance for pig farmers provided by OMAFRA [50] as well as peer reviewed studies in the case of some important co-products[23] (see supplementary S3 material for further detail on ingredient inclusion limits)

The retention of N in finished pigs was calculated using the principles of Wellock et al [51] and was assumed to be 0.0256 BW ± 0.00128. Retention of P and K were calculated using an isometric relationship of body composition to BW [52] and were assumed to be approximately 0.005 BW ± 0.00025 and 0.002 BW ± 0.0001 respectively. For K this assumption represents a linear approximation around slaughter weight of a curvilinear relationship [53]. All N, P and K not retained by the finished pigs were assumed to be excreted in faeces or urine. The predicted levels of nutrient excretion were required as inputs to the manure model.

Diets formulated

The process followed to formulate G/F diets for environmental impact objectives is shown as part of figure 2. The average NRRU, AP, EP and GWP per kg of each ingredient as seen in table 1 were added to the list of ingredient properties in the diet formulation tool. As well as this, equations which predicted the average environmental impact per kg of N, P and K excretion assuming an average mix of manure management practices were extracted from the manure sub-model of the LCA[5]. This enabled the tool to account for the environmental impact resulting from predicted levels of nutrient excretion when formulating the diets. Thus for any diet formulated the average NRRU, AP, EP and GWP resulting from the feed supply chain and manure storage and application was predicted.

The tool was used to formulate G/F diets for both economic and environmental impact objectives. Two diets were formulated for economic objectives: 1) to minimise feed cost per kg live weight (LW) gain (least cost) and 2) to minimise feed cost per kg LW gain with a requirement to maintain a certain level of feed efficiency (least cost EFF). The NE content of the latter diet was fixed, so that feed: LW gain ratio was minimised within reasonable commercial constraints. The minimum specifications of this diet were the “industry standard” energy and nutrient levels shown in table 2. This is a common commercial scenario, whereby diets are formulated for least cost without compromising feed efficiency [1]. This diet was included to quantify whether this strategy has any benefit for the environmental impact of the system compared to considering feed cost alone.

Four diets were formulated to minimise the individual environmental impact categories NRRU, AP, EP and GWP. A further diet was formulated to minimise the combined environmental impact (least EI) of the G/F phase, as measured using the combined normalised levels of NRRU, AP, EP and GWP under the CML methodology [39] with equal weighting. All diets formulated for environmental impact objectives were restricted to a 30%

maximum cost increase in comparison to the least feed cost diet. Diets were formulated for these objectives in both regional scenarios for ingredient prices and ingredient availability for Eastern and Western Canada. Diets were formulated using linear programming. The resulting diets were optimal solutions based on the mean nutritional and environmental impact properties of the ingredients, as well as the mean impact levels associated with nutrient excretion calculated by the LCA.

Dietary comparisons in the LCA model

Accounting for the uncertainty in LCA is important to produce credible and reliable results [54]. In this study an uncertainty analysis was used for statistical comparison of the diet formulations. The cradle to farm gate LCA model was hosted in the specialist software SimaPro. All input parameters had a mean, associated distribution (e.g. normal, lognormal etc.) and standard deviation. The uncertainty in the environmental impact calculations was quantified using Monte-Carlo simulations [5]. Variability in all characteristics of herd performance other than feed intake was assumed to be independent of feed composition in the G/F production stage. Feed intake for each simulation was a function of the energy density of the diet in relation to the average energy requirement of the herd over the G/F production stage. This requirement had a distribution to represent variation in feed intake due to genetic and environmental factors, which were assumed to be independent of the feed composition.

As shown in figure 2 each diet was tested in the cradle to farm-gate LCA of pig farming systems in Eastern and Western Canada. In each case 1000 simulations of the model were run in order to calculate the NRRU, AP, EP and GWP of the system when adopting these diets. This number of simulations ensured the SEM of the results for each impact category were low enough for good repeatability [5]. Parallel Monte-Carlo simulations were used to compare all other diets to the least cost diet. The parallel simulations enabled the model to determine whether diets had resulted in any significant changes to the environmental impact levels of the system compared to the least cost scenario. This method of uncertainty analysis to distinguish between 2 scenarios in an LCA model was described in detail in Mackenzie et al [5]. Briefly uncertainties were categorised as either specific to the system (α) or shared between the systems being compared (β) [55,56]. For each simulation a value for each parameter was randomly selected from the specified distribution input for this variable. Where parameters are shared between two scenarios being tested (for example maize yield (kg/hectare) when feeding two different diets containing maize), for each individual comparison the same point on the distribution is selected. In this case variation in all parameters except the G/F diet composition, the resulting feed intake and nutrient excretion during the G/F phase and carcass yield were considered shared uncertainty in the comparisons. While the average energy requirement was variable to account for differences caused by animal and environmental factors, in each comparison the NE intake was the same for both diets. The key output of the simulations was the frequency in which the environmental impact of one scenario was greater or smaller than the second scenario for each impact category tested. Environmental impact levels were reported as significantly different in cases where $P < 0.05$ over 1000 parallel simulations of the LCA model. This allowed the model to account for shared uncertainty between two systems (in this case diets) modelled in the LCA, but provide a useful answer as to which is likely to have greater environmental impact.

Results

Diet composition

The overall ingredient and nutritional composition of the diets formulated for Eastern and Western Canada are in tables 3 and 4 respectively, along with the predicted feed cost and average feed intake per pig for each diet. For both regional scenarios the least cost diet had the lowest nutritional density and thus the highest average predicted feed intake over the G/F cycle of the diets formulated. The least cost EFF diet minimised feed intake (by design) and was cheaper per kg LW than all diets formulated for environmental impact objectives.

Of the diets formulated for environmental impact objectives the least NRRU diets was the most expensive in both regions, resulting in a 30% increase in feed cost in comparison to the least cost diet. The least GWP diets also resulted in large increases in feed cost per kg LW of 30% and 23% in the East and West Canadian scenarios respectively. The least NRRU and least GWP diets raised feed costs significantly due to increased inclusions of relatively expensive protein meals (soya meal and canola meal). The least AP increased feed costs by 12% in Eastern Canada and 16% in Western Canada compared to the least cost diet. The least EI diets were 12% more expensive than the least cost diet in both regions. The Least EP diet was the cheapest of the diets formulated for environmental impact objectives, increasing feed costs by 8% and 6% compared to the least cost diet in Eastern and Western Canada respectively.

In both regions the least GWP diet was the most energy dense of all the diets formulated for environmental impact objectives (along with the least EI diet in the east), with feed intake the same as the least cost EFF diet. The West Canadian least EI diet was less energy dense and thus average feed intake per pig was higher at 274 kg in comparison to 264 kg per pig in the Eastern scenario. The least EP diet reduced average feed intake by 3% in the Eastern scenario and 6% reduced average feed intake in the West. Compared to the least cost diet average feed intake was 5% lower for the least AP diet in the East Canadian scenario and 4% in the West. The least NRRU diets were the least nutritionally dense of the environmental impact objective diets with feed intake 2% lower in the east and 4% lower in the west in comparison to the least cost diet.

The least cost EFF diet contained the largest amount of cereals (maize in the east and wheat/barley in the west) of all diets formulated. In both regions this diet contained the lowest levels of co-products (such as maize DDGS and wheat shorts), as well as an increased combined inclusion of oilseed meals (canola meal and soy meal) compared to the least cost diet. All diets formulated for environmental impact objectives in Eastern Canada included the maximum allowed levels of bakery meal in the G/F diets. Similarly with the exception of the least NRRU diet, all diets formulated for environmental impact objectives in Eastern Canada contained the maximum amount of wheat bran. This was not the case for the wheat/barley based diets formulated in the Western Canada.

In both regions the least NRRU diet contained the lowest combined inclusion of whole cereals (wheat, barley and maize). The least NRRU diet contained no synthetic amino acid supplements or maize DDGS in either regions. In both regions the least GWP and least NRRU diets were very similar: both contained high levels of wheat shorts and, in the East, bakery meal and meat meal. There was also an increased inclusion of soymeal in the least GWP diets with very little synthetic amino acid supplementation compared to the least cost formulation.

Environmental Impacts – Eastern Canada

The environment impact results per kg of CW from cradle to farm gate for the East Canadian diets when tested in the LCA model are in table 5. The relative trade-offs of diets formulated for different objectives in terms of environmental impact, feed cost and feed intake are shown in figure 3 for Eastern Canada. The least cost EFF diet reduced NRRU and GWP by 8% and 3% respectively compared to the least cost diet; levels of AP and EP were not significantly different between these two scenarios. The combined environmental impact score of the least cost EFF diet was marginally lower than the least cost diet by <1%.

Reductions in NRRU (48%), AP (5%), EP (6%) and GWP (17%) were made when diets were formulated to minimise these impact categories in comparison to the least cost diet. The maximum reduction achieved in the combined environmental impact score was 5% when optimising the G/F diets for this objective compared to the least cost diet. In each case diets aimed at minimising the individual environmental impact categories resulted in increases in some of the other impact categories tested, compared to the least cost diet. The least NRRU diet also reduced GWP by 14%, but increased AP and EP by 45 and 48% respectively. Similarly the least GWP diet increased AP by 26%, EP by 28% and NRRU 45%. The least AP diet increased NRRU by 19%, whilst EP was reduced by 5% with no significant difference in GWP. The least EP diet also meant that AP was 5% lower, however NRRU and GWP increased by 13 % and 3% respectively. The least EI diet did not increase any of the four environmental impact categories tested, the only diet formulated to achieve this.

Environmental Impacts - Western Canada

The environment impact results per kg of CW from cradle to farm gate for the diets in Western Canada when tested in the LCA model are in table 6. The relative trade-offs of diets formulated for different objectives in terms of environmental impact, feed cost and feed intake are shown in figure 4 for Western Canada. The least feed cost EFF diet resulted in a 6% increase in NRRU and 4% lower levels of AP while EP and GWP did not change. The combined environmental impact score of the least cost EFF diet was 3% lower than the least cost diet.

Reductions in NRRU (45%), AP (15%), EP (5%) and GWP (22%) were made when diets were formulated to minimise these impact categories in comparison to the least cost diet. A 5% reduction was made in the combined environmental impact score per kg of CW when this was the objective. Diets optimised to minimise the individual environmental impact categories resulted in increases in some of the other impact categories tested, compared to the least cost formulation. The least NRRU diet also reduced GWP by 19% but increased AP and EP by 30 and 31% respectively. Similarly the least GWP diet increased AP by 15%, EP by 23% with NRRU up 35% compared to the least cost diet. The least AP diet increased NRRU by 30% and did not significantly alter EP or GWP. The least EP diet meant that AP was 1.5% lower, however NRRU increased by 12 % with no significant change in GWP. The least EI diet in the West reduced AP (14%), but did increase NRRU by (18%) with no significant difference in EP or GWP compared to the least cost formulation.

Discussion

As feed production and manure management are the main sources of environmental impact for pig production systems [5,6,13,16], it is logical to consider diet formulation as a mechanism to reduce the environmental impact of pig production. In this study we formulated diets for the G/F production stage as this is where the majority of feed intake occurs per finished pig [5]. There is also potential to formulate sow diets for environmental impact objectives to make reductions to the environmental impact of pig production systems. Although previous analysis of the farming systems modelled here showed that proportion of environmental impacts from this production phase is ~15% per kg ECW for most impact categories [5]. Previous LCA studies have used scenario testing to demonstrate the potential for dietary changes to reduce the environmental impact of non-ruminant livestock systems [12,21,56–58]. In this study we used a different approach by developing a novel methodology which integrated a cradle to farm-gate LCA model into a diet formulation tool to formulate diets for specific environmental impact objectives. Methodologies such as this one can allow nutritionists to integrate environmental impact objectives into diet formulations and for livestock producers to quantify the environmental impact of different feeding strategies. The methodology was associated with several challenges that are discussed below. The effectiveness of the methodology as a tool to reduce the environmental impacts of pig production systems and the strategies it identified to achieve this are then addressed.

Methodological Challenges

1) *Accounting for environmental impacts caused by ingredient choice, as well as nutrient excretion*

Previous LCA studies using life cycle inventory data to formulate diets which minimise the environmental impacts per kg of diet [59,60] have not taken into account the implications for nutrient excretion and the resulting environmental impacts. Predicting nutrient excretion is a common step in diet formulation. There are equations which can be integrated within animal growth models to predict nutrient excretion for a larger range of scenarios, using a more mechanistic approach than the one adopted in this paper [1,61]. Previous studies have formulated diets where minimising nutrient excretion or levels of methane emissions were explicit objectives, as a way of incorporating environmental goals into least cost formulation [62,63]. These studies however, did not adopt a holistic LCA approach to quantify whether reductions in these specific emissions reduced the cradle to farm gate environmental impacts of the production system. The method developed in this paper accounted for the aggregated environmental impacts during manure management caused by N, P and K excretion when formulating diets for environmental impact objectives. It predicted the feed intake required for pigs to reach a target weight with any N, P and K not retained by the animal excreted in the urine or faeces. A component of an LCA of pig farming systems was integrated into the diet formulation algorithm to predict the NRRU, AP, EP and GWP which resulted from the storage and application to land of excreted nutrients as manure [23]. This included an estimate of the potential of the nutrients contained in the manure produced to replace mineral fertilizers being applied to field in crop systems, an approach known as system expansion [64]. This approach incorporates the potential benefits of replacing mineral fertilizers with manure as well as accounting for the extra emissions this may cause. To our knowledge this is the first time a diet formulation tool using a holistic LCA approach from cradle to farm gate has been developed to formulate livestock diets for environmental impact objectives.

2) Formulating diets for multiple environmental impact objectives

When formulating diets for environmental impact objectives in livestock systems, adopting a single metric is necessary in order to optimise diets for this purpose using linear programming. However diets formulated to minimise one impact category may cause large increases in another type of environmental impact. If multiple environmental impact categories are to be accounted for when using linear programming a combined environmental impact score must be defined. Combining environmental impacts in a meaningful way is a significant methodological challenge to LCA practitioners; its subjective nature means there is little agreement on how best to approach it [65]. Here the CML global normalisation methodology was adopted, there are many more complex methods for combining impacts which give various weightings to different types of impact [66,67] but these methods are still based on subjective allocations of importance to the different impact categories. Such weightings are not currently recommended in the ISO standard for Life Cycle Impact Assessment [65,68]. It was not the purpose of this study to advance the discussion on how best to weigh environmental impacts. Any solution produced to minimise a metric for combined environmental impact is dependent on the methodology used to quantify it. Subjective choices such as which impact categories are included and how these categories are then weighted (to name only two) will hugely influence the outcome. The step of combining the impact categories provided the formulation tool with a framework to assess the trade-offs between decreases in one type of environmental impact and increases in another. Some methodologies have monetised the environmental impact categories using either the preferences of a panel, or the authors stated preferences to give a monetary value to different impact categories [(69,70)]. Further work to define acceptable methodologies for the monetisation of environmental impacts would enhance efforts to reduce the environmental impact of livestock systems. This could allow feed cost and environmental impacts to be integrated into a single objective to formulate diets which are economically and environmentally more sustainable.

3) *Allowing flexibility in the diet formulation rules to identify the optimal nutritional strategies for environmental impact objectives.*

Previous studies which have formulated diets for environmental impact objectives have done so for a fixed minimum nutritional specification for energy (MJ/kg) and nutrient content (g/kg) above which feed intake was assumed not to be affected [(59,60)]. This is a fairly restrictive way to formulate diets and there is no consideration of the trade-off between environmental impact per kg of feed and feed intake. In this study the formulation algorithm accounted for the expected effect of energy density on feed intake and identified the optimum energy density across each feeding phase for a particular impact objective. This approach is common in commercial diet formulation as maximising gain to feed will not always result in the optimum outcome in terms of feed cost or other economic objectives [(1)]. This was evident in the diets formulated to minimise feed cost per kg LW gain were the least energy dense of all diets formulated in this study. Livestock diets have not been previously formulated for environmental impact objectives using this flexible approach to the nutritional density of the solution.

In this study improving gain: feed on a least cost basis reduced the environmental impacts of the farming system, as shown by the least cost EFF diet in both regions having a lower combined environmental impact score than the least cost diets. The diets formulated for least NRRU, AP and EP however, did not maximise gain: feed in both the East and West Canadian scenario. The optimum energy density of the G/F diet was also different for each of the impact objectives. Similarly the least EI diets in the scenarios for Eastern and Western Canada also had differing energy densities, showing the need for flexibility when formulating diets for environmental impact objectives depending on the available ingredients. Formulating diets for a fixed minimum nutritional specification at an assumed feed intake would have restricted the ability of the tool to minimise both individual environmental impact categories, and the combined environmental impact score of the system. This is the first study to present a diet formulation algorithm which has the flexibility to identify the optimal nutritional density of livestock diets for different environmental impact objectives. The study demonstrated how environmental impact objectives can be integrated into modern diet formulation tools. The integration of diet formulation and LCA could be utilised to weigh the relative costs of reducing specific types of environmental impact from modern pig farms through diet manipulation. The approach could also be used to help modern pig production systems adapt and limit their liability to environmental taxes imposed on them.

Formulation strategies for environmental impact reduction

In most cases (with the exception of EP in the east and AP in the west) diets formulated for environmental impact objectives had a lower total inclusion of whole cereals (maize, wheat or barley) than diets formulated for economic objectives. This is because when formulating diets for environmental impact objectives, the environmental "cost" of production compared to the nutritional profile of these cereals is less favourable than their market value. When available, bakery meal was included at (or close to) maximum allowed levels in all diets formulated for environmental impact objectives. Bakery meal has relatively low levels of environmental impacts in the categories tested, and high nutritional value as an ingredient in diets fed to growing pigs (although there are concerns about its variability) [50]. Apart from these two examples there were few uniform trends observed in the strategies adopted for different environmental impact objectives.

When minimising NRRU and GWP, high protein diets were formulated with increased inclusions of soya meal and co-products such as wheat shorts, wheat bran and meat meal. Amino acid supplementation was not utilised when minimising NRRU and GWP. This contrasted with previous studies, conducted mainly in Europe, suggesting low protein diets with amino acid supplementation as a method of reducing GWP in pig production systems [21,58,71]. The reason for the difference is the majority of soya meal used in European animal feed is imported from South America [72] and is associated with recent land use change which carries a significant environmental impact penalty. Similarly, maize DDGS was also excluded from the least GWP and least NRRU diets because its production is associated with high levels of these impact categories (table 1), due to energy inputs for drying and processing [22]. Previous LCA studies have also found that including maize DDGS in pig diets increased GWP in pig farming systems [16,23,73].

In order to minimise AP and EP diets were formulated with increased amino acid supplementation to minimise crude protein content. Other studies which have used scenario testing to assess the effect of amino acid supplementation in pig diets on the systems environmental impacts make similar conclusions [21,58]. The results from both regions showed that increased inclusions of maize DDGS can be used as part of balanced G/F diets to minimise EP and AP in pig farming systems. This finding contradicts previous studies that individually tested the effect of including DDGS in Canadian pig diets [23]. The reason for the contradiction is due to differences in formulation objectives, with previous studies formulating for least cost rather than formulating for environmental impact objectives. This highlights the advantage of explicitly formulating pig diets for environmental impact objectives. A diet formulation algorithm can be used to formulate a balanced solution that includes ingredients which reduce the overall levels of a particular impact category, while simultaneously accounting for the trade-off between changes in feed intake and potential reductions in the environmental impacts per kg of the diet fed.

Effectiveness of optimisation as a strategy to reduce environmental impact in pig systems

The results of this study showed that through optimising G/F diets specifically for the purpose of reducing the environmental impact of pig production, it is possible to reduce the overall levels of NRRU, AP, EP and GWP in both maize and wheat/barley based diets. Relatively large proportional reductions were shown to be possible in the levels of NRRU and GWP in both regions when optimising to minimise the impacts individually. However, due to increases in EP and AP these diets increased the combined environmental impact score of the system. Such outcomes can only be considered a reduction in the environmental impact of the system if environmental impact categories other than the objective (e.g. GWP) are considered unimportant. This is difficult to justify in the case of pig farming systems which have been shown to cause relatively small levels of GWP compared to meat produced from ruminants [9–11]. The results show the importance of considering multiple impact categories when using linear programming to optimise diets to reduce the environmental impacts of livestock systems.

Optimising G/F diets to minimise the combined environmental impact score resulted in relatively modest reductions (~5%) for the pig farming system in both regions. Cost was not the limiting factor for further reduction of the combined environmental impact score of the system; as the least EI diets in both regions were below the 30% increase limit on feed cost. Further reductions in the combined environmental impact score through diet optimisation were restricted by the contrasting formulation strategies required to minimise NRRU and GWP compared to those for AP and EP. The solutions for least NRRU and least GWP were high protein diets which included large amounts of low value co-products. Whereas the diets for least EP and AP, minimised dietary protein content and increased levels of amino acid and mineral supplementation. However production of these ingredients had high NRRU and GWP. This meant the possible reductions in the combined environmental impact score were much lower than those for individual environmental impact categories such as GWP or NRRU.

There are examples of policies using financial penalties or rewards to provide economic incentives for livestock producers to reduce their environmental impacts. These have included taxes on spreading fertilizers in the EU [74] and payments to farmers for reducing the greenhouse gas emissions caused by farming activities in Australia (the carbon farming initiative) [75]. Methodologies like the one presented here, could be used to evaluate how livestock producers might adapt formulation strategies under such mechanisms, and whether these changes would reduce the cradle to farm gate environmental impact of livestock systems for a particular impact category. It is also possible to carry out sensitivity analyses in order to estimate the necessary levels of penalty or payments to incentivise changes which reduce the levels from cradle to farm gate by x% for a given impact category.

Conclusions

A modified diet formulation algorithm was designed which integrated important elements of an existing LCA model into a linear program for diet formulation, in order to formulate G/F diets for environmental impact objectives. The flexibility of this approach allowed it to identify the optimum nutritional composition of the diets for a particular environmental impact objective as well as altering the ingredient composition. The optimum energy density of the G/F diet was different for each of the environmental impact objectives. Through optimising diets for individual environmental impact categories relatively large reductions in NRRU and GWP were found to be possible compared to the least feed cost diet, however these came at the expense of increases in AP and EP. The results showed that the easy solution to minimise environmental impacts is not always to feed a low energy by product based diet. This was demonstrated by the least GWP diets, which in both regions were the most energy dense along with the least cost EFF diets. Diets were also formulated to minimise a combined environmental impact score for NRRU, AP, EP and GWP which enabled reductions in the environmental impacts of the system without any large increases in individual impact categories. Further work to define acceptable methodologies to combine and monetise different categories of environmental impact, could allow feed cost and environmental impacts to be integrated into a single objective. This would allow nutritionists to formulate diets which are economically and environmentally more sustainable. This study demonstrated how environmental impact objectives can be integrated into modern diet formulation tools for livestock production systems using LCA.

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Conflicts of interest

None.

Authorship

This paper derives from the doctoral thesis of SM under the supervision of IK, IL and NF. All authors contributed to designing the formulation tool and the scenarios to be tested. SM constructed the diet formulation tool, formulated the diets and conducted the LCA model simulations. All authors contributed to the interpretation of the outcomes and the reporting of the paper.

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Table 1. Average environmental impacts per kg for all feed ingredients included in grower/finisher diets tested. Inventory data for these ingredients was compiled as part of a previous life cycle assessment studies of Canadian pig farming systems [5,23].

Impact category [*]	**NRRU**	**AP**	**EP**	**GWP**	**Combined environmental impact score** [†]
Unit [‡]	**kg Sb eq**	**kg SO2 eq**	**kg PO4 eq**	**kg CO2 eq**	**<no units>**
Barley	2.18E-03	5.36E-03	2.69E-03	0.38	8.20E-14
Canola meal	1.39E-03	7.97E-03	1.59E-03	0.30	8.53E-14
Canola oil	3.84E-03	2.20E-02	4.40E-03	0.84	2.36E-13
Maize	1.71E-03	5.13E-03	1.11E-03	0.39	6.55E-14
Soya meal	5.70E-04	4.11E-03	8.71E-04	0.15	4.33E-14
Wheat	1.84E-03	1.01E-02	2.04E-03	0.43	1.10E-13
Meat (pork) meal	1.05E-03	2.46E-04	6.16E-05	0.13	1.21E-14
Maize DDGS	6.51E-03	1.13E-03	2.66E-04	0.78	7.05E-14
Wheat Bran	1.02E-03	5.56E-03	1.12E-03	0.24	6.07E-14
Wheat shorts	5.12E-04	2.78E-03	5.59E-04	0.12	3.03E-14
Field Peas	1.32E-03	2.31E-03	2.72E-03	0.58	5.98E-14
Bakery meal	5.17E-04	1.41E-03	2.60E-04	0.08	1.73E-14
Animal-vegetable fat blend	2.57E-03	1.01E-02	2.06E-03	0.49	1.16E-13
Soy Oil	1.51E-03	1.09E-02	2.30E-03	0.40	1.15E-13
HCL-Lysine	3.51E-02	2.12E-02	9.97E-03	4.81	5.68E-13
L-Threonine	3.51E-02	2.12E-02	9.97E-03	4.81	5.68E-13
FU-Methionine	3.64E-02	7.54E-03	1.70E-03	2.95	3.71E-13
L-Tryptophan	7.01E-02	4.24E-02	1.99E-02	9.62	1.14E-12
Sodium Chloride	1.21E-03	8.97E-04	6.68E-04	0.18	2.36E-14
Dicalcium Phosphate	9.40E-03	2.68E-02	3.63E-04	1.51	2.91E-13
Limestone	1.31E-04	1.03E-04	3.58E-05	0.02	2.33E-15

[*] NRRU, Non-renewable resource use. AP, Acidification Potential. EP, Eutrophication Potential, GWP, Global Warming Potential.

[†] Calculated by combining the total normalised NRRU, AP, EP and GWP using the CML methodology [39] with equal weighting

[‡] eq, equivalent

Table 2 The nutritional specifications of the "typical" grower/finisher diet for Canadian pig systems. The lower limits permitted in the diet formulation rules used in this study are also shown.

Resource (g/kg unless otherwise stated)	Starter		Grower		Finisher		Late finisher	
	Typical	Lower Limit	Typical	Lower Limit	Typical	Lower Limit	Typical	Lower Limit
Net Energy (MJ/kg)	10.21	9.70	9.89	9.40	9.72	8.99	9.65	8.93
Dig Crude Protein	156.3	148.5	140.5	133.5	122.9	113.7	110.1	101.8
Dig Arg	10.5	10.0	8.8	8.3	7.2	6.7	6.3	5.8
Dig His	4.7	4.4	4.1	3.9	3.5	3.2	3.1	2.9
Dig Ile	6.1	5.8	5.3	5.1	4.6	4.3	4.0	3.7
Dig Leu	12.8	12.1	12.1	11.5	11.4	10.5	10.4	9.6
Dig Lys	10.4	9.9	9.2	8.7	7.3	6.8	6.5	6.0
Dig Met	3.2	3.0	2.7	2.6	2.5	2.3	2.2	2.0
Dig Phe	7.2	6.8	6.4	6.1	5.7	5.3	5.1	4.7
Dig Thr	6.3	6.0	5.8	5.5	4.9	4.5	4.4	4.1
Dig Trp	1.7	1.6	1.5	1.4	1.2	1.1	1.1	1.0
Dig Val	7.3	6.9	6.5	6.2	5.8	5.4	5.1	4.7
Dig Cys	2.7	2.6	2.7	2.6	2.5	2.3	2.3	2.1
Dig Meth + Cys	5.9	5.6	5.5	5.2	5.1	4.7	4.5	4.2
Ca	7.6	7.2	7.6	7.2	6.7	6.2	5.9	5.5
P	5.5	5.2	5.3	5.0	4.6	4.3	4.1	3.8
Dig P	3.1	2.9	2.8	2.7	2.3	2.1	1.9	1.8
K	6.6	6.3	6.2	5.9	5.6	5.2	5.0	4.6

862 **Table 3** The overall ingredient and nutritional composition (across all 4 feeding phases) of
863 grower/finisher diets formulated for different objectives for Eastern Canada. All ingredient
864 inclusion and nutrient levels shown are g/kg as fed unless otherwise stated. The average
865 predicted feed intake and feed costs for each grower/finisher diet are also shown

Objective*	**Least cost**	**Least cost EFF**	**Least NRRU**	**Least AP**	**Least EP**	**Least GWP**	**Least EI**
Average feed cost (CAD/ kg live weight gain)	0.544	0.562	0.708	0.610	0.591	0.708	0.611
Average feed consumed (kg/pig)	280.5	264.0	275.8	265.4	272.5	264.0	264.0
Ingredient							
Canola Meal	42.77	51.05	100.00	95.69	96.39	0.00	71.18
Maize	574.99	706.29	232.13	443.17	580.35	237.67	480.57
Maize DDGS	36.79	0.00	0.00	113.88	53.10	0.00	0.00
Meat meal	0.00	0.00	39.83	0.00	0.00	40.99	0.00
Bakery Meal	0.00	0.00	94.01	94.08	94.24	94.05	94.05
Soymeal High Protein	88.67	169.88	250.00	46.51	62.38	250.00	109.81
Wheat	0.00	0.00	0.00	0.00	25.63	0.00	0.00
Wheat Bran	0.00	0.00	0.00	50.00	50.00	50.00	50.00
Wheat shorts	231.29	45.11	261.53	86.64	0.00	260.60	136.25
Limestone	13.46	12.40	13.06	22.48	19.78	26.52	22.03
Dicalcium Phosphate	0.86	3.73	0.00	0.54	2.09	0.00	0.29
NaCl	4.22	4.77	2.41	3.22	2.92	3.19	3.41
Lysine HCL	2.35	0.86	0.00	3.70	3.35	0.00	2.18
DL Methionine	0.11	0.06	0.00	0.12	0.15	0.02	0.22

L Threonine	0.48	0.08	0.00	0.80	0.81	0.00	0.57
L Tryptophan	0.00	0.00	0.00	0.02	0.01	0.00	0.00
Soy Oil	0.00	0.00	0.00	0.00	0.00	19.00	15.81
AV fat blend	0.00	1.49	2.96	34.91	4.68	13.70	9.37
Additives	4.01	4.26	4.08	4.24	4.13	4.26	4.26
Resource							
Net Energy (MJ/kg)	9.24	9.82	9.39	9.77	9.51	9.82	9.82
Dig CP	127.7	145.15	213.7	128.7	125.5	192.5	134.7
Dig Arg	8.6	10.1	16.3	7.8	7.6	14.8	9.2
Dig His	4.0	4.8	7.0	3.7	3.7	6.3	4.2
Dig Ile	5.0	6.0	9.0	4.8	4.7	8.1	5.3
Dig Leu	11.7	13.3	16.8	12.0	11.6	15.3	11.5
Dig Lys	7.5	8.0	11.8	8.0	7.8	10.5	8.0
Dig Met	2.4	2.6	3.6	2.6	2.5	3.1	2.6
Dig Phe	6.2	7.2	10.3	6.0	5.8	9.4	6.4
Dig Thr	4.9	5.2	7.6	5.1	5.0	6.7	5.2
Dig Trp	1.4	1.6	2.7	1.3	1.3	2.4	1.6
Dig Val	6.2	6.9	10.5	6.1	5.8	9.4	6.4
Dig Cys	2.4	2.6	3.6	2.5	2.5	3.1	2.6
Dig Meth + Cys	4.9	5.2	7.2	5.1	5.0	6.2	5.1
Ca	6.5	6.9	9.9	10.2	9.4	14.5	10.0
P	5.2	4.8	7.8	5.1	4.7	7.3	5.0
Dig P	2.7	2.5	4.4	2.6	2.3	4.2	2.4
K	7.0	6.7	10.5	6.5	5.8	9.8	6.9
Gross Energy (MJ/kg)	16.7	16.3	17.3	17.4	16.4	17.6	17.0
Crude protein	165.5	175.4	271.3	166.3	156.6	242.5	170.4

Ash	45.5	42.2	60.7	57.6	52.4	69.8	57.9

* Least Cost, least feed cost per kg live weight gain. Least cost EFF, least cost / kg Live weight gain while maximising feed efficiency within commercial constraints. NRRU, Non-renewable resource use. AP, Acidification Potential. EP, Eutrophication Potential. GWP, Global Warming Potential. Least EI, least combined environmental impact score.

Table 4 The overall ingredient and nutritional composition (across all 4 feeding phases) of grower/finisher diets formulated for different objectives for Western Canada. All ingredient inclusion and nutrient levels shown are g/kg as fed unless otherwise stated. The average predicted feed intake and feed costs for each grower/finisher diet are also shown

Objective*	Least cost	Least cost EFF	Least NRRU	Least AP	Least EP	Least GWP	Least EI
Average feed cost (CAD/ kg live weight gain)	0.536	0.550	0.690	0.623	0.567	0.656	0.599
Average feed consumed (kg/pig)	283.1	264.0	271.4	272.2	266.4	264.4	274.4
Ingredient							
Barley	0.00	0.00	0.00	579.38	0.00	353.32	489.80
Canola Meal	38.61	52.00	77.97	3.05	0.00	61.03	0.00
Maize DDGS	83.09	112.34	0.00	179.26	145.46	0.00	164.05
Meat meal	0.00	0.00	1.01	0.00	0.00	0.27	0.00
Field Peas	100.00	100.00	100.00	13.81	0.00	0.00	12.05
Soymeal HP	5.40	13.95	250.00	59.35	34.67	250.00	57.03
Wheat	553.94	606.49	279.81	0.00	518.81	0.00	0.00
Wheat Bran	0.00	0.00	0.00	42.80	0.00	0.00	0.00
Wheat shorts	177.93	48.82	261.53	37.67	209.32	260.49	190.87
Limestone	12.59	11.67	11.21	21.75	25.52	22.03	24.12
Dicalcium	2.71	6.11	0.00	0.55	2.40	0.00	0.21

Phosphate							
NaCl	3.97	4.14	4.54	3.65	4.10	4.69	3.57
Lysine HCL	2.94	3.44	0.00	3.60	4.50	0.00	3.35
DL Methionine	0.05	0.08	0.00	0.19	0.13	0.00	0.15
L Threonine	0.47	0.66	0.00	0.77	0.88	0.00	0.68
L Tryptophan	0.00	0.00	0.00	0.04	0.00	0.00	0.01
Soy Oil	0.00	0.00	0.00	7.80	14.55	0.00	20.00
AV fat blend NRC	14.30	36.07	9.82	42.20	35.45	43.91	30.00
Additives	4.00	4.26	4.10	4.14	4.23	4.26	4.10
Resource							
Net Energy (MJ/kg)	9.20	9.82	9.55	9.52	9.79	9.80	9.45
Dig CP	139.6	145.2	238.8	134.2	138.6	196.3	132.8
Dig Arg	8.5	8.4	18.1	7.6	7.8	14.7	8.0
Dig His	3.7	3.8	7.6	3.6	3.7	6.4	3.7
Dig Ile	5.2	5.4	10.0	4.8	5.1	8.2	4.8
Dig Leu	10.8	11.5	17.6	11.1	11.4	14.4	11
Dig Lys	7.5	8.0	13.4	7.8	7.9	10.7	7.7
Dig Met	2.4	2.6	3.8	2.5	2.6	3.1	2.5
Dig Phe	6.7	7.0	11.5	6.5	6.8	9.7	6.5
Dig Thr	4.8	5.2	8.4	5.0	5.1	6.9	5.0
Dig Trp	1.5	1.6	3.0	1.3	1.5	2.5	1.3
Dig Val	6.4	6.5	11.4	6.2	6.4	9.5	6.3
Dig Cys	3.0	3.1	4.2	2.5	2.9	3.4	2.5
Dig Meth +	5.4	5.7	8.1	5.0	5.5	6.5	4.9

Cys							
Ca	6.4	6.9	6.7	9.5	11.2	10.6	10.3
P	5.6	5.7	7.4	4.8	5.6	6.2	5.2
Dig P	2.3	2.4	3.5	2.5	2.4	3.1	2.8
K	7.0	6.4	11.3	7.1	7.1	10.4	7.7
Gross Energy (MJ/kg)	16.5	16.7	17.3	17.6	17.3	17.8	17.8
Crude protein	179.3	180.9	297.7	170.1	178.1	246.3	174.4
Ash	45.2	43.4	53.2	51.6	57.3	64.3	56.7

* Least Cost, least feed cost per kg live weight gain. Least cost EFF, least cost / kg Live weight gain while maximising feed efficiency within commercial constraints. NRRU, Non-renewable resource use. AP, Acidification Potential. EP, Eutrophication Potential. GWP, Global Warming Potential. Least EI, least combined environmental impact score.

Table 5 The environmental impacts per kg of Carcass Weight for grower/finisher diets in Eastern Canada formulated for different objectives.

Impact category*	Unit†	Least Cost	Least Cost EFF	Least NRRU	Least AP	Least EP	Least GWP	Least EI
NRRU	kg Sb eq	0.0063	0.0058	0.0033	0.0075	0.0071	0.0035	0.0054
AP	kg SO_2 eq	0.0548	0.0555[NS]	0.0799	0.0520	0.0523	0.0688	0.0532
EP	kg PO_4 eq	0.0140	0.0140[NS]	0.0208	0.0133	0.0132	0.0179	0.0135
GWP	kg CO_2 eq	2.09	2.03	1.80	2.14[NS]	2.15	1.73	1.91
CML Environmental impact score	<no units>	3.67E-13	3.65E-13	4.70E-13	3.62E-13	3.60E-13	4.13E-13	3.49E-13

* Least Cost, least feed cost per kg live weight gain. Least cost EFF, least cost / kg Live weight gain while maximising feed efficiency within commercial constraints. NRRU, Non-renewable resource use. AP, Acidification Potential. EP, Eutrophication Potential. GWP, Global Warming Potential. Least EI, least combined environmental impact score.

† eq, equivalent

[NS] = Not significantly different from the Least Cost diet (P>0.05)

Table 6 The environmental impacts per kg of Carcass Weight for grower/finisher diets in Western Canada formulated for different objectives.

Impact category*	Unit†	Least Cost	Least cost EFF	Least NRRU	Least AP	Least EP	Least GWP	Least EI
NRRU	kg Sb eq	0.00797	0.00848	0.00427	0.0102	0.0086	0.0050	0.0093
AP	kg SO_2 eq	0.0648	0.0624	0.0827	0.0535	0.0604	0.0703	0.0540
EP	kg PO_4 eq	0.0167	0.0160^{NS}	0.0214	0.0162^{NS}	0.0150	0.0193	0.0160^{NS}
GWP	kg CO_2 eq	2.31	2.33^{NS}	1.87	2.30^{NS}	2.23	1.75	2.21^{NS}
CML Environmental impact score	<no units>	4.34E-13	4.22E-13	4.91E-13	4.09E-13	4.10E-13	4.38E-13	4.02E-13

* Least Cost, least feed cost per kg live weight gain. Least cost EFF, least cost / kg Live weight gain while maximising feed efficiency within commercial constraints. NRRU, Non-renewable resource use. AP, Acidification Potential. EP, Eutrophication Potential. GWP, Global Warming Potential. Least EI, least combined environmental impact score.

† eq, equivalent

^{NS} = Not significantly different from the Least Cost diet (P>0.05)

Figure 1 The structure and main components of the pig production systems as considered by the Life Cycle Assessment model. Feed production in the model included the manufacture of fertilisers and pesticides etc. as inputs to growing crops.

Figure 2 Schematic of the methodology followed in this study to formulate diets for environmental impact objectives.

Figure 3 The environmental impacts, feed cost and feed intake per kg of Carcass Weight for grower/finisher diets in Eastern Canada formulated for different objectives, represented as a fraction of the results for the least cost diet. Least cost = least feed cost per kg live weight gain, Least cost EFF = least cost / kg Live weight gain while maximising feed efficiency within commercial constraints, NRRU = Non-renewable resource use, AP = Acidification Potential EP = Eutrophication Potential, GWP = Global Warming Potential. Least EI = least combined environmental impact score.

Figure 4 The environmental impacts, feed cost and feed intake per kg of Carcass Weight for grower/finisher diets in Western Canada formulated for different objectives, represented as a fraction of the results for the least cost diet. Least cost = least feed cost per kg live weight gain, Least cost EFF = least cost / kg Live weight gain while maximising feed efficiency within commercial constraints, NRRU = Non-renewable resource use, AP = Acidification Potential EP = Eutrophication Potential, GWP = Global Warming Potential. Least EI = least combined environmental impact score.

Figure 1.

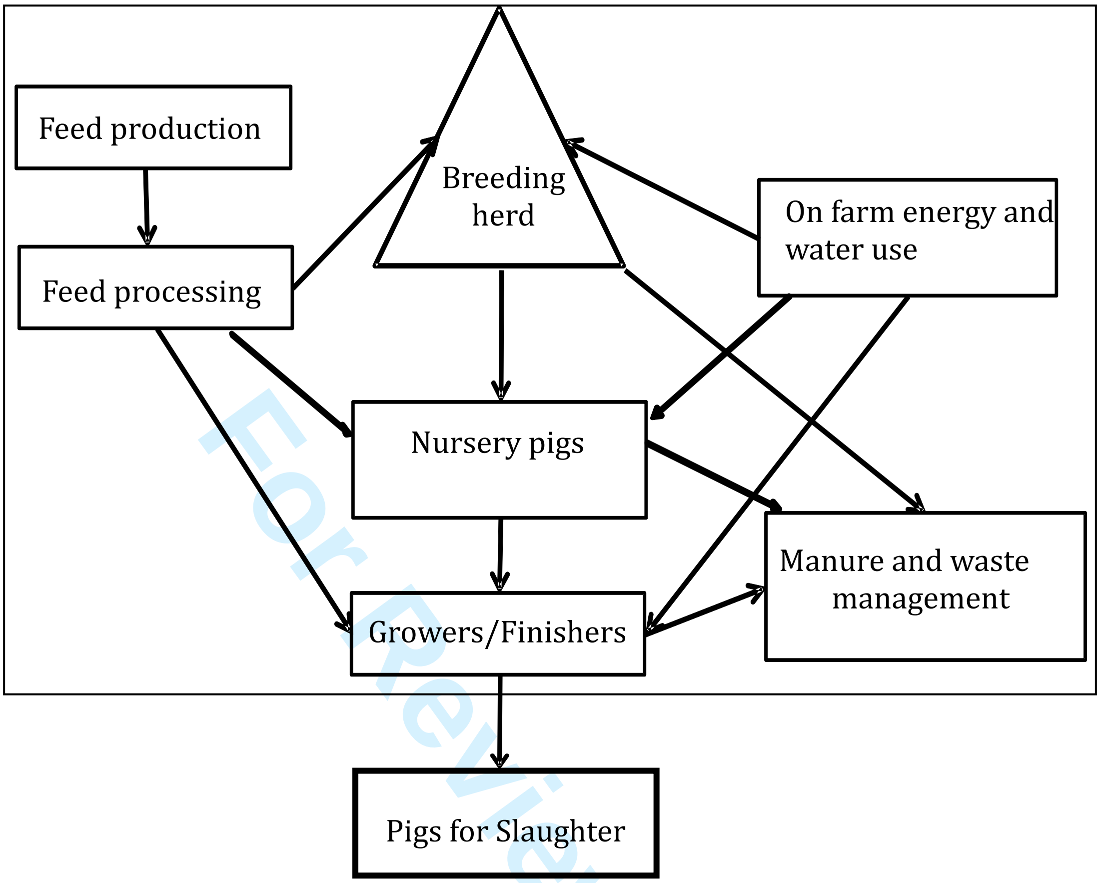
Feed production
Breeding herd
On farm energy and water use
Feed processing
Nursery pigs
Manure and waste management
Growers/Finishers
Pigs for Slaughter

Figure 2.

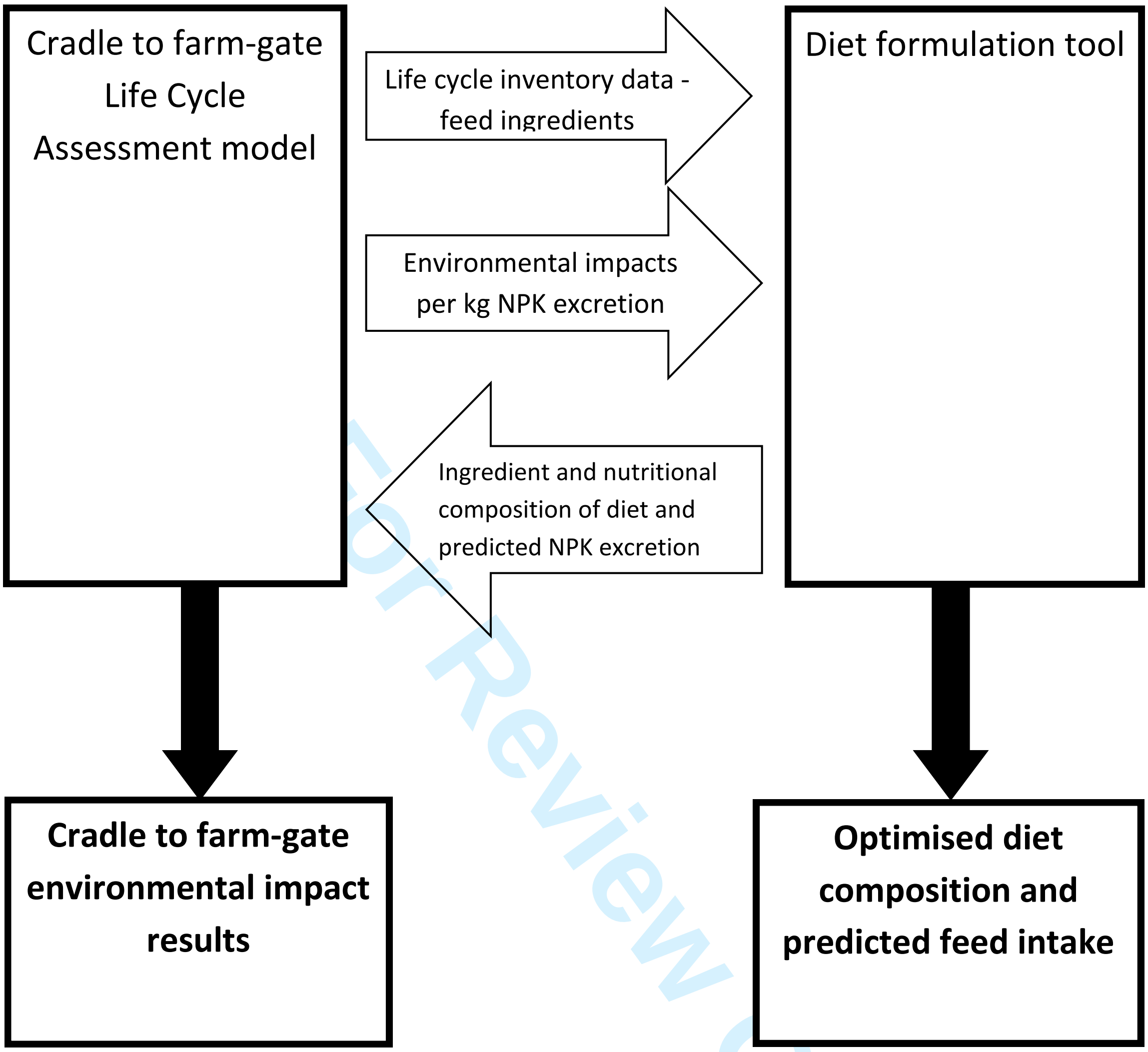
Cradle to farm-gate Life Cycle Assessment model
Life cycle inventory data - feed ingredients
Environmental impacts per kg NPK excretion
Ingredient and nutritional composition of diet and predicted NPK excretion
Diet formulation tool
Cradle to farm-gate environmental impact results
Optimised diet composition and predicted feed intake

Figure 3

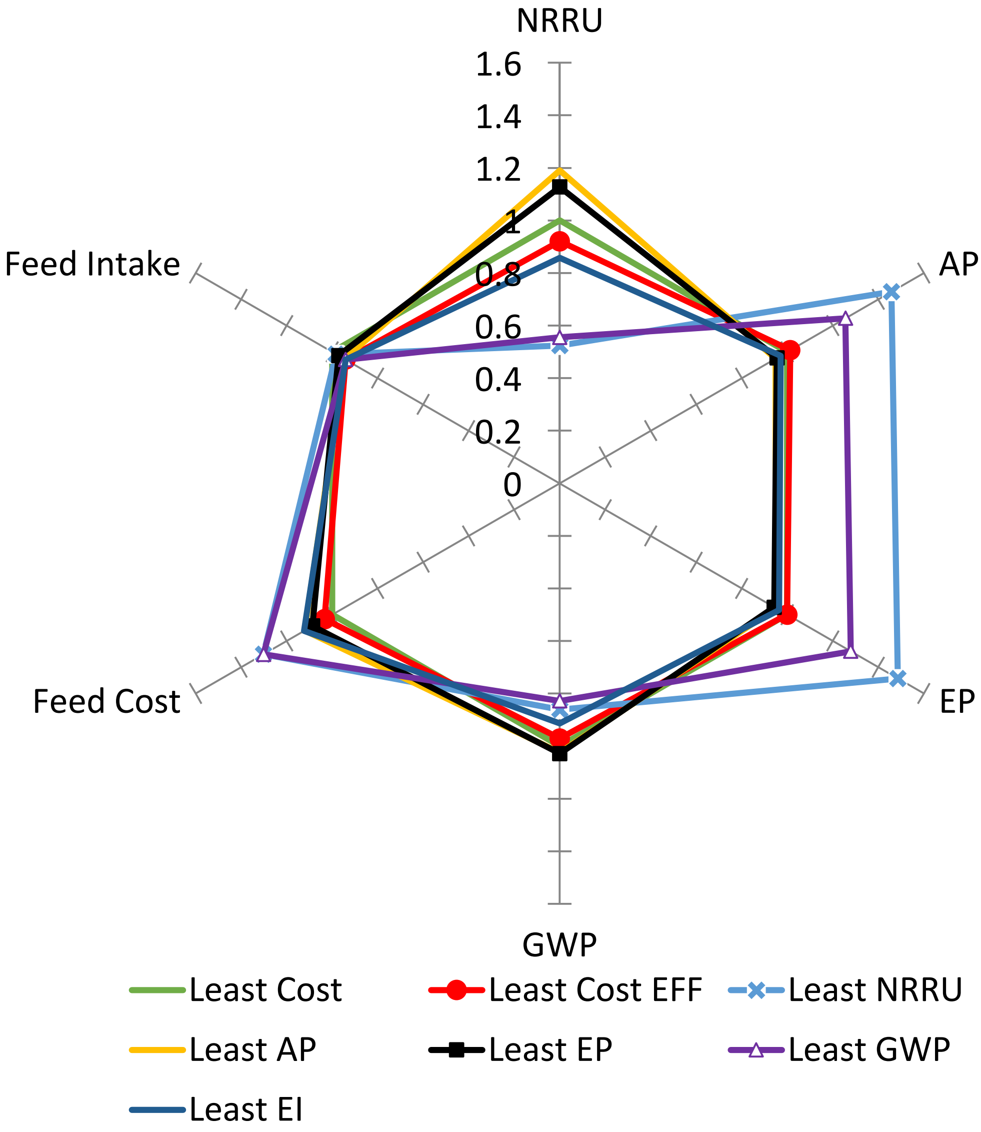
NRRU
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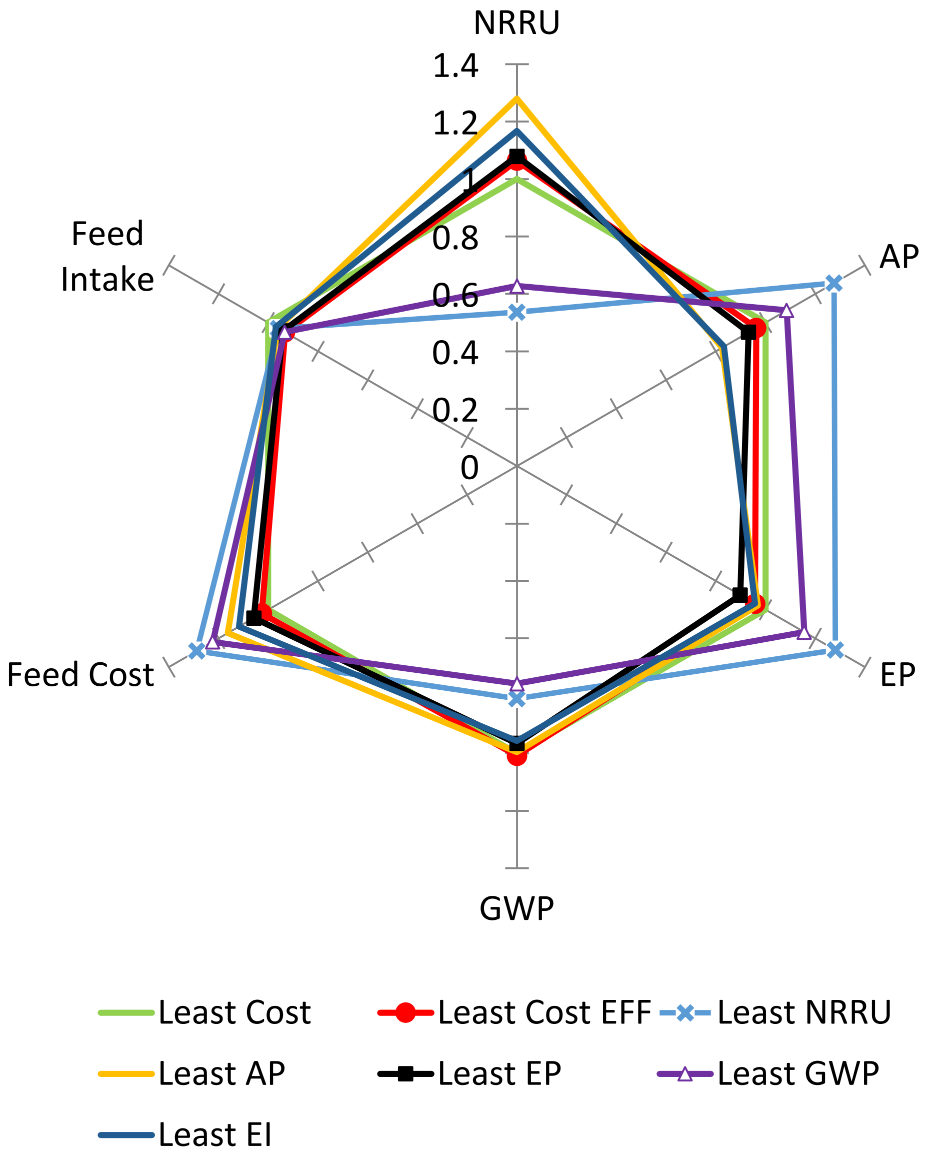
Figure 4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Least NRRU
Least AP
Least EP
Least GWP
Least EI

Towards a methodology to formulate sustainable diets for livestock: accounting for environmental impact in diet formulation – Supplementary material

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Supplement S1 – Co Product Allocation

Table S1 Allocation factors used for multioutput processes in the feed supply chain

Multioutput system	By products	Mass yield (%)	Price Ratio †	Allocation (%)
Soybean Oil extraction[1]	Soybean meal	77.3	1	43.7
	Soybean Oil	22.7	2.64	56.3
Canola Oil extraction[1]	Canola Meal	57.3	1	32.8
	Canola Oil	42.6	2.76	67.2
Bioethanol production from corn[2]	Ethanol			97.6
	Corn DDGS			2.4
Wheat Flour mill[3]	Flour	73	1††	89.8
	Wheat Shorts	12.5	0.22	3.4
	Wheat Bran	12	0.44	6.5
	Wheat Germ	2.0	0.11	0.27
Industrial Bakery ‡	Bread	92	10	99
	Bakery waste	8	1	1
Fat Rendering[4]	Fat	57.7	1.22	62.6
	Meat Meal	42.3	1	37.4

† Price data average Canadian (not regionalised) prices for 2013 provided by Trouw Nutrition based on Statistics Canada price data [5]

‡ Expert advice from Sugarich (specialist producers of animal feed using bakery waste products, 2015

†† Flour price was estimated using the principle that sales of flour provide around 90% of the gross margin for typical wheat flour milling operations [6].

Supplement S2 – Regional price ratios used for diet formulation

Table S2 price ratios used for diet formulation, all prices scaled to the price of wheat which = 1 per tonne. Average ingredient prices and availability in Ontario and Manitoba for 2015 were provided by Trouw Nutrition (derived from Statistics Canada data [7]).

Ingredient	Price Ratio – Eastern Canada	Price Ratio – Western Canada
Barley	0.79	1.01
Bakery meal	1.00	NA
Canola meal	1.46	1.56
Corn	0.75	NA
Corn DDGS	0.98	1.21
Field Peas	N/A	1.17
Meat (pork) meal	2.46	2.88
Soya meal	1.93	2.43
Wheat	1.00	1.19
Wheat Bran	1.46	1.90
Wheat shorts	0.73	0.89
Animal-vegetable fat blend	3.25	3.43
Canola oil	13.9	NA
Soy Oil	4.22	4.42
HCL-Lysine	8.17	10.5
L-Threonine	17.7	25.7
FU-Methionine	18.0	30.2
L-Tryptophan	89.3	121
Sodium Chloride	0.31	0.72
Dicalcium Phosphate	2.71	3.39
Limestone	0.44	0.64

Supplement S3 – Ingredient inclusion limits

Table S3 The maximum inclusion limits (g/kg as fed) of the ingredients for each feeding phase when formulating grower/finisher diets in this study. These limits were based on guidance for pig farmers provided by OMAFRA [(8)] as well as peer reviewed studies in the case of some important co-products [(5)].

Ingredient	Starter	Grower	Finisher	Late finisher
Barley	800	800	800	800
Bakery meal	50	100	100	100
Canola meal	100	100	100	100
Corn	800	800	800	800
Corn DDGS	150	200	200	200
Field Peas	100	100	100	100
Meat (pork) meal	50	50	50	50
Soya meal	250	250	250	250
Wheat	700	700	700	700
Wheat Bran	50	50	50	50
Wheat shorts	200	300	300	200
Animal-vegetable fat blend[1]	50	50	50	50
Canola oil[1]	20	20	20	20
Soy Oil[1]	20	20	20	20
HCL-Lysine	10	10	10	10
L-Threonine	10	10	10	10
FU-Methionine	10	10	10	10
L-Tryptophan	10	10	10	10
Sodium Chloride	10	10	10	10
Dicalcium Phosphate	50	50	50	50
Limestone	50	50	50	50

[1] Total fat supplementation was restricted to 50 g/kg as fed in all diets

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